

APPENDIX D

Partition Coefficients For Cesium

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D.1.0 Background

Three generalized, simplifying assumptions were established for the selection of cesium K_d values for the look-up table. These assumptions were based on the findings of the literature reviewed we conducted on the geochemical processes affecting cesium sorption. The assumptions are as follows:

- Cesium adsorption occurs entirely by cation exchange, except when mica-like minerals are present. Cation exchange capacity (CEC), a parameter that is frequently not measured, can be estimated by an empirical relationship with clay content and pH.
- Cesium adsorption onto mica-like minerals occurs much more readily than desorption. Thus, K_d values, which are essentially always derived from adsorption studies, will greatly overestimate the degree to which cesium will desorb from these surfaces.
- Cesium concentrations in groundwater plumes are low enough, less than approximately 10^{-7} M, such that cesium adsorption follows a linear isotherm.

These assumptions appear to be reasonable for a wide range of environmental conditions. However, these simplifying assumptions are clearly compromised in systems with cesium concentrations greater than approximately 10^{-7} M, ionic strengths greater than about 0.1 M, and pH values greater than about 10.5. These assumptions will be discussed in more detail in the following sections.

Based on the assumptions and limitation described above, cesium K_d values and some important ancillary parameters that influence cation exchange were collected from the literature and tabulated. Data included in this table were from studies that reported K_d values (not percent adsorbed or Freundlich or Langmuir constants) and were conducted in systems consisting of:

- Low ionic strength (< 0.1 M)
- pH values between 4 and 10.5
- Dissolved cesium concentrations less than 10^{-7} M
- Low humic material concentrations (< 5 mg/l)
- No organic chelates (*e.g.*, EDTA)

The ancillary parameters included in these tables were clay content, mica content, pH, CEC, surface area, and solution cesium concentrations. This cesium data set included 176 cesium K_d values.

Two separate data sets were compiled. The first one (see Section D.3) included both soils and pure mineral phases. The lowest cesium K_d value was 0.6 ml/g for a measurement made on a system containing a soil consisting primarily of quartz, kaolinite, and dolomite and an aqueous phase consisting of groundwater with a relatively high ionic strength ($I \approx 0.1$ M) (Lieser *et al.*, 1986) (Table D.1). The value is unexplainably much less than most other cesium K_d values present in the data set. The largest cesium K_d value was 52,000 ml/g for a measurement made on a pure vermiculite solid phase (Tamura, 1972). The average cesium K_d value was 2635 ± 530 ml/g.

Table D.1. Descriptive statistics of cesium K_d data set including soil and pure mineral phases. [Data set is presented in Section D.3.]

	K_d (ml/g)	Clay (%)	Mica (%)	pH	CEC (meq/100 g)	Surface Area (m ² /g)
Mean	2,635	30	5.5	7.4	30.4	141.3
Standard Error	530	3.8	0.7	0.1	3.7	29.7
Median	247	42	4	8.2	4.8	31.2
Mode	40	42	4	8.2	1.8	17.7
Standard Deviation	7055	15	4.4	1.7	37.4	230.4
Sample Variance	49,781,885	226	20.0	2.8	1,396.9	53,106
Range	51,999	38	13	7.8	129.9	638
Minimum	0.6	4	2	2.4	0.00098	8
Maximum	52,000	42	15	10.2	130	646
No. Observations	177	15	41	139	103	60
Confidence Level (95.0%)	1,046.6	8.3	1.4	0.3	7.3	59.5

A second data set (see Section D.4) was created using only data generated from soil studies, that is, data from pure mineral phases, and rocks, were eliminated from the data set. Descriptive statistics of the soil-only data set are presented in Table D.2. Perhaps the most important finding of this data set is the range and median¹ of the 57 K_d values. Both statistics decreased appreciably. In the soil-only data set, the median was 89 ml/g. The median is perhaps the single central estimate of a cesium K_d value for this data set. The range of K_d values was from 7.1 ml/g, for a measurement made on a sandy carbonate soil (Routson *et al.*, 1980), to 7610 ml/g for a measurement made on another carbonate soil containing greater than 50 percent clay and silt (Serne *et al.*, 1993). Interestingly, these 2 soils were both collected from the U.S. Department of Energy's Hanford Site in eastern Washington state.

Table D.2. Descriptive statistics of data set including soils only. [Data set is presented in Section D.4.]

	Cesium K_d (ml/g)	Clay (%)	Mica (%)	pH	CEC (meq/100g)	Surface Area (m²/g)
Mean	651	5	5.6	6.9	34	57.5
Standard Error	188	0.6	0.6	0.3	8.9	13.4
Median	89	5.0	4	6.7	20	60
Mode	22	NA	4	4.0	60	70
Standard Deviation	1423	1.0	4.3	1.9	29.5	44.6
Sample Variance	2026182	1.0	18.4	3.6	870	1986
Range	7602	2.0	13	7.8	57.4	123.4
Minimum	7.1	7.1	2	2.4	2.6	6.6
Maximum	7610	6.0	15	10.2	70.0	130
No. Observations	57	3	45	55	11	11
Confidence Level (95%)	378	2.5	1.29	0.5	19.8	30

¹ The median is that value for which 50 percent of the observations, when arranged in order of magnitude, lie on each side.

The soil-only data set was frequently incomplete with regard to supporting data describing the experimental conditions under which the cesium K_d values were measured (Table D.2). Quite often the properties of the solid phase or the dissolved cesium concentration used in the K_d experiments were not reported. For instance, there were only 3 cesium K_d values that had accompanying clay content data, 11 cesium K_d values that had accompanying cation exchange data, and 11 cesium K_d values that had accompanying surface area data (Table D.2). Consequently, it was not possible to evaluate adequately the relationship between cesium K_d values and these important, independent soil parameters. This is discussed in greater detail below.

D.2.0 Approach and Regression Models

D.2.1 Correlations with Cesium K_d Values

A matrix of the correlation coefficients for the parameters included in the data set containing K_d values determined in experiments with both soils and pure mineral phases is presented in Table D.3. The correlation coefficients that are significant at or less than the 5 percent level of probability ($P \leq 0.05$) are identified with a footnote. The parameter with the largest correlation coefficient with cesium K_d was CEC ($r = 0.52$). Also significant was the correlation coefficient between cesium K_d values and surface area ($r = 0.42$) and CEC and clay content ($r = 0.64$). The poor correlation between cesium aqueous concentration ($[Cs]_{aq}$) and cesium K_d values can be attributed to the fact that the former parameter included concentration of the solution prior and after contact with the soils. We report both under the same heading, because the authors frequently neglected to indicate which they were reporting. More frequently, the spike concentration (the cesium concentration prior to contact with the soil) was reported, and this parameter by definition is not correlated to K_d values as well as the concentrations after contact with soil (the denominator of the K_d term).

A matrix of the correlation coefficients for the parameters included in the data set containing K_d values determined in experiments with only soils is presented in Table D.4. As mentioned above (Table D.2), the reports in which soil was used for the K_d measurements tended to have little supporting data about the aqueous and solid phases. Consequently, there was little information for which to base correlations. This occasionally resulted in correlations that were not scientifically meaningful. For example, the correlation between CEC and cesium K_d was -0.83, for only 11 observations (10 degrees of freedom). The negative sign of this correlation contradicts commonly accepted principles of surface chemistry.

Table D.3. Correlation coefficients (r) of the cesium K_d value data set that included soils and pure mineral phases. [Data set is presented in Section D.3.]

	Cesium K_d	Clay Content	Mica	pH	CEC	Surface Area
Cesium K_d	1.00					
Clay Content	0.05	1.00				
Mica	0.29	0.00	1.00			
pH	0.10	-0.11	0.08	1.00		
CEC	0.52 ^a	0.64 ^a	NA	0.37	1.00	
Surface Area	0.42 ^a	0.35	NA	-0.11	0.47 ^a	1.00
$[Cs]_{aq}$	-0.07	0.85 ^a	0.29	0.13	-0.17	-0.15
a Correlation coefficient is significant at the 5% level of significance ($P \leq 0.05$).						

Table D.4. Correlation coefficients (r) of the soil-only data set. [Data set is presented in Section D.4.]

	Cesium K_d	Clay Content	Mica	pH	CEC	Surface Area
Cesium K_d	1.00					
Clay Content	-0.21	1.00				
Mica	0.27	0	1.00			
pH	0.11	0.4	0.07	1.00		
CEC	-0.83	NA	0.99 ¹	0.05	1.00	
Surface Area	-0.31	NA	0.99 ¹	-0.03	0.37	1.00
$[Cs]_{aq}$	0.18	NA	0.09	-0.04	0.00	0
¹ Correlation coefficient is significant at >5% level of significance ($P \leq 0.05$).						

The high correlations between mica concentrations and CEC ($r = 0.99$) and mica concentrations and surface area ($r = 0.99$) are somewhat misleading in the fact that both correlations represent only 4 data points collected from 1 study site in Fontenay-aux-Roses in France (Legoux *et al.*, 1992).

D.2.2 Cesium Adsorption as a Function of CEC and pH

Akiba and Hashimoto (1990) showed a strong correlation between cesium K_d values and the CEC of a large number of soils, minerals, and rock materials. The regression equation generated from their study was:

$$\log (Cs K_d) = 1.2 + 1.0 \log (CEC) \quad (D.1)$$

A similar regression analysis using the entire data set (mineral, rocks, and soils) is presented in Figure D.1.

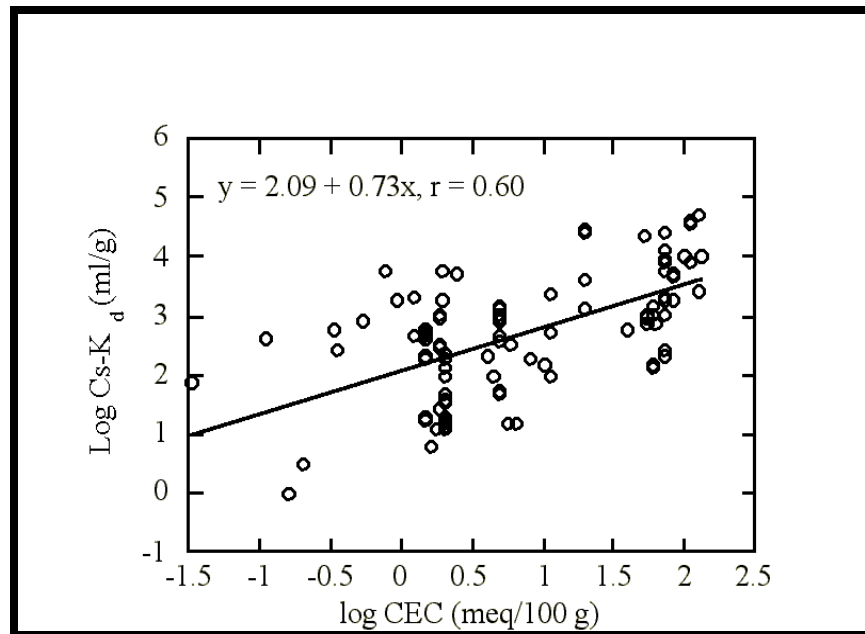


Figure D.1. Relation between cesium K_d values and CEC.

By transposing the CEC and cesium K_d data into logarithms, the regression correlation slightly increases from 0.52 (Table D.3) to 0.60 (Figure D.1). However, a great amount of scatter in the data can still be seen in the logarithmic transposed data. For instance, at $\log(\text{CEC})$ of 0.25, the cesium K_d values range over 4 orders of magnitude. It is important to note that the entire cesium K_d data set only varies 5 orders of magnitude. Thus, the correlation with CEC, although the strongest of all the independent variables examined, did not reduce greatly the variability of possible cesium K_d values.

D.2.3 CEC as a Function of Clay Content and pH

Because CEC values are not always available to contaminant transport modelers, an attempt was made to use independent variables more commonly available in the regression analysis. Multiple regression analysis was conducted using clay content and pH as independent variables to predict CEC values (Figure D.2). Clay content was highly correlated to CEC ($r = 0.64$). Soil pH was not significantly correlated to either CEC or cesium K_d values.

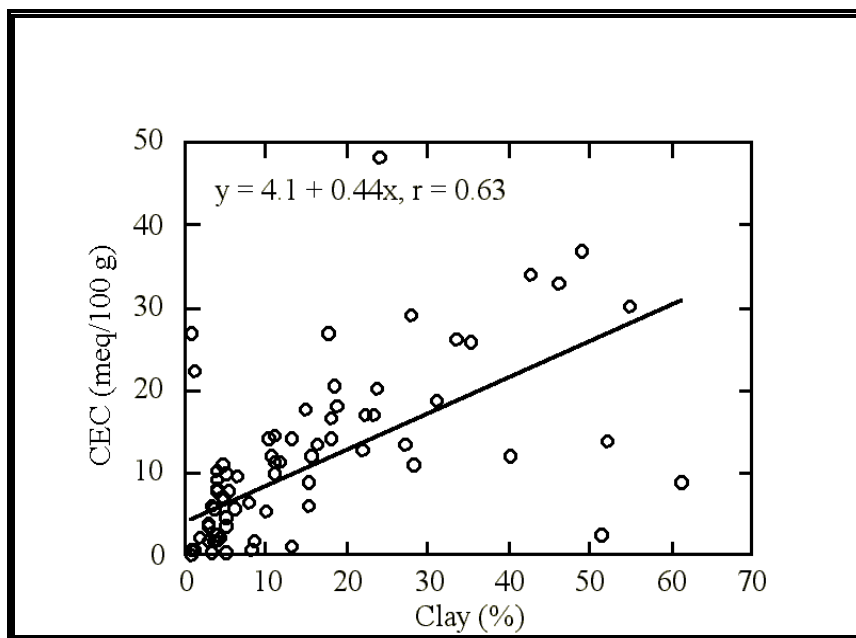


Figure D.2. Relation between CEC and clay content.

D.2.4 Cesium Adsorption onto Mica-Like Minerals

Cesium adsorption onto mica-like minerals has long been recognized as a non-reversible reaction (Bruggenwert and Kamphorst, 1979; Comans *et al.*, 1989; Cremers *et al.*, 1988; Douglas, 1989; Evans *et al.*, 1983; Francis and Brinkley, 1976; Sawhney, 1972; Smith and Comans, 1996; Tamura, 1972). This is an important property in adsorption reactions because 1 of the assumptions in applying the K_d model to describe adsorption is that the rate at which adsorption occurs is equal to the rate at which desorption occurs. This phenomena is referred to as an adsorption hysteresis. Cesium adsorption onto mica-like minerals is appreciably faster than its desorption. The reason for this is that the cesium ion fits perfectly into the hexagonal ring formed on the tetrahedral sheet in the crystallographic structure of mica-like clays. This perfect fit does not permit other cations that exist at much greater concentrations in nature to exchange the cesium from these sites. This can be demonstrated using the data of Tamura (1972) (Table D.5). He measured cesium K_d values for mica, vermiculite, and kaolinite using a water and 0.1 M NaCl background solution. For mica, the K_d value remained about the same for both solutions. For the vermiculite and kaolinite, the cesium K_d values greatly decreased when the higher ionic strength solution was used. This indicates that the sodium, which existed at 11 orders of magnitude higher concentration than the cesium could out compete the adsorption of cesium on the vermiculite and kaolinite but not on the mica. Another point of interest regarding this data set is that the cesium K_d values do correlate with CEC of these different mineral phases when water is the background solution. However, when the higher ionic strength solution is used, the correlation with CEC no longer exists.

Comans *et al.* (1989) measured cesium K_d values of a mica (Fithian illite) by desorption and adsorption experiments. Portions of their data are presented in Table D.6. Cesium K_d values based on desorption experiments are appreciably greater than those measure in adsorption experiments.

Table D.5. Effect of mineralogy on cesium exchange. [Data are from Tamura (1972) who used an initial concentration of dissolved cesium of 1.67×10^{-12} M.]

Mineral Phases	CEC (meq/100 g)	K_d in Water (ml/g)	K_d in 0.1 M NaCl (ml/g)
Mica	20	26,000	28,600
Vermiculite	127	52,000	2,700
Kaolinite	11.2	2,500	94

Table D.6. Cesium K_d values measured on mica (Fithian illite) via adsorption and desorption experiments. [Data are from Comans *et al.* (1989).]

Experimental Conditions	Adsorption Cesium K_d	Desorption Cesium K_d
K-saturated Mica, 7×10^{-6} M Cs	2,890	5,200
K-saturated Mica, 2×10^{-7} M Cs	9,000	11,300
Ca-saturated Mica, 7×10^{-6} M Cs	1,060	4,600
Ca-saturated Mica, 2×10^{-7} M Cs	600,000	1,050,000

Essentially all K_d values reported in the literature are measured using adsorption experiments. Thus, in the case of soils containing mica-like soils, using adsorption K_d values will likely overestimate the degree to which desorption will occur. To account for this difference in adsorption and desorption, one could artificially increase the K_d values used in a transport code when cesium is desorbing from contaminated soil.

D.2.5 Cesium Adsorption as a Function of Dissolved Cesium Concentrations

At very low concentrations, the adsorption isotherm for cesium is linear. The linear range varies dependent on the adsorbing phase and on the background aqueous phase (Akiba *et al.*, 1989; Sposito, 1989). Table D.7 provides the linear range of some Freundlich adsorption isotherm data reported in the literature. The upper limit of the linear range varies by several orders of magnitude depending on the solid phase and aqueous chemistry. The lowest upper limit reported in Table D.7 is 1×10^{-10} M cesium. This is in fact a rather high concentration when compared to those found in groundwater plumes. For instance, the highest reported ^{137}Cs concentration in the groundwaters beneath the Hanford Site in 1994 was 1.94×10^{-13} M (or 2,310 pCi/l) for Well 299 E-28-23 (Hartman and Dresel, 1997). This is several orders of magnitude below the smallest upper limit reported in Table D.7, suggesting that most far-field radioactive cesium adsorption likely follows a linear isotherm. The simple K_d value describes a linear isotherm.

Table D.7. Approximate upper limits of linear range of adsorption isotherms on various solid phases.

Upper Limit of Linear Range (M)	Solid Phase	Background Aqueous Phase	Reference
1×10^{-7}	Itado Tuff	Deionized Water	Akida <i>et al.</i> , 1989
1×10^{-10}	Sandstone	Deionized Water	Akida <i>et al.</i> , 1989
5×10^{-5}	Limestone	Deionized Water	Akida <i>et al.</i> , 1989
1×10^{-10}	Augite Andesite	Deionized Water	Akida <i>et al.</i> , 1989
5×10^{-9}	Olivine Basalt	Deionized Water	Akida <i>et al.</i> , 1989
1×10^{-8}	Rokko Granite	Deionized Water	Akida <i>et al.</i> , 1989
5×10^{-8}	Biotite	Deionized Water	Akida <i>et al.</i> , 1989
5×10^{-7}	Albite	Deionized Water	Akida <i>et al.</i> , 1989
1×10^{-6}	K-Feldspar	Deionized Water	Akida <i>et al.</i> , 1989
1×10^{-1}	Unwashed Kaolinite	Distilled Water/pH 10	Adeleye <i>et al.</i> , 1994
$<1 \times 10^{-5}$	Ca Montmorillonite	Distilled Water/pH 10	Adeleye <i>et al.</i> , 1994
$<1 \times 10^{-5}$	Na Montmorillonite	Distilled Water/pH 10	Adeleye <i>et al.</i> , 1994
$<1 \times 10^{-5}$	Na Kaolinite	Distilled Water/pH 10	Adeleye <i>et al.</i> , 1994
1×10^{-3}	Na Montmorillonite	Distilled Water/pH 4	Adeleye <i>et al.</i> , 1994

When a wider range of cesium concentrations are considered, cesium adsorption onto soils and pure minerals has been reported to be almost without exception a non-linear relationship (Adeleye *et al.*, 1994; Akiba *et al.*, 1989; Ames *et al.*, 1982; Erten *et al.*, 1988; Konishi *et al.*, 1988; Lieser and Staunton, 1994; Steinkopff, 1989; Torstenfelt *et al.*, 1982). Most investigators have used a Freundlich equation to describe this relationship (Adeleye *et al.*, 1994; Konishi *et al.*, 1988; Shiao *et al.*, 1979; Staunton, 1994; Torstenfelt *et al.*, 1982). The Freundlich equation is

$$C_{s_{\text{absorbed}}} = a (C_{s_{\text{solution}}})^b \quad (\text{D.2})$$

where $C_{s_{\text{absorbed}}}$ and $C_{s_{\text{solution}}}$ are the cesium concentrations adsorbed and in solution, respectively, and a and b are fitting parameters. A short description of those Freundlich Equation reported in the literature are presented in Table D.8. The descriptive statistics of the Freundlich Equations

reported in Table D.8 are described in Table D.9. A plot of available cesium adsorption versus equilibrium cesium solution concentration is shown in Figure D.3.

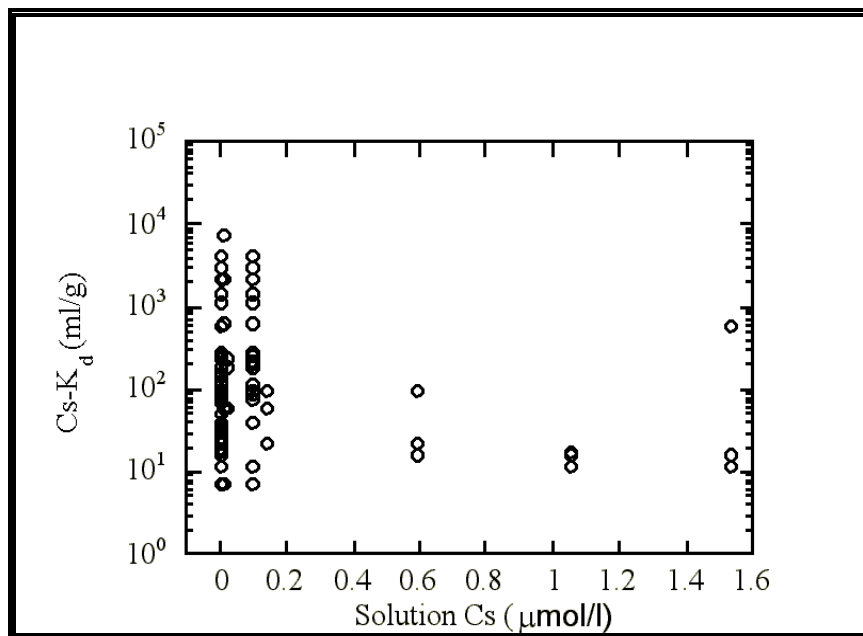


Figure D.3. K_d values calculated from an overall literature Freundlich equation for cesium (Equation D.2).

Table D.8. Freundlich equations identified in literature for cesium.

a¹	b¹	Range of Solution Cs Concentration (M)	Experimental	Ref.²
1.7	0.677		Water/Batcombe Sediment	1
3,300	0.909		Water/Denchworth Sediment	1
260	0.841		Water/Tedburn Sediment	1
16	0.749		Water/Teigngrace Sediment	1
12.2	0.745	1×10^{-8} to 1×10^{-12}	Water/Batcombe Sediment	1
6,070	0.899	1×10^{-8} to 1×10^{-12}	Water/Denchworth Sediment	1
1,290	0.849	1×10^{-8} to 1×10^{-12}	Water/Tedburn Sediment	1
163	0.815	1×10^{-8} to 1×10^{-12}	Water/Teigngrace Sediment	1
1.23	0.657	1×10^{-8} to 1×10^{-12}	CaCl ₂ /Batcombe Sediment	1
0.63	0.659		CaCl ₂ /Batcombe Sediment	1
427	0.814	1×10^{-8} to 1×10^{-12}	CaCl ₂ /Denchworth Sediment	1
1.5	0.599		CaCl ₂ /Denchworth Sediment	1
48.1	0.754	1×10^{-8} to 1×10^{-12}	CaCl ₂ /Tedburn Sediment	1
17	0.739		CaCl ₂ /Tedburn Sediment	1
5.22	0.702	1×10^{-8} to 1×10^{-12}	CaCl ₂ /Teigngrace Sediment	1
4.4	0.716		CaCl ₂ /Teigngrace Sediment	1
0.22	1.1	1×10^{-9} to 1.5×10^{-2}	Bentonite/Water	2
0.017	0.53	1×10^{-9} to 1.5×10^{-2}	Bentonite/Water	2
0.13	1	1×10^{-9} to 1.5×10^{-2}	Bentonite/Groundwater	2
0.048	0.67	1×10^{-9} to 1.5×10^{-2}	Bentonite/Groundwater	2
5.10×10^{-4}	0.21	1×10^{-9} to 1.5×10^{-2}	Takadata Loam/Water	2
3.00×10^{-3}	0.48	1×10^{-9} to 1.5×10^{-2}	Takadata Loam/Groundwater	2
1.30×10^{-5}	0.013	1×10^{-9} to 1.5×10^{-2}	Hachinohe Loam/Water	2
2.30×10^{-5}	0.38	1×10^{-9} to 1.5×10^{-2}	Hachinohe Loam/Groundwater	2

a¹	b¹	Range of Solution Cs Concentration (M)	Experimental	Ref.²
2.70x10 ⁻⁴	0.546	1x10 ⁻⁸ to 1x10 ⁻²	Unwashed/Kaolinite/pH 2	3
5.20x10 ⁻⁴	0.543	1x10 ⁻⁸ to 1x10 ⁻²	Unwashed/Kaolinite/pH 4	3
2.04x10 ⁻³	0.588	1x10 ⁻⁸ to 1x10 ⁻²	Unwashed/Kaolinite/pH 10	3
2.27x10 ⁻³	0.586	1x10 ⁻⁸ to 1x10 ⁻²	Sodium/Kaolinite/pH 2	3
5.04x10 ⁻²	0.723	1x10 ⁻⁸ to 1x10 ⁻²	Sodium/Kaolinite/pH 4	3
3.49x10 ⁻²	0.703	1x10 ⁻⁸ to 1x10 ⁻²	Na/Kaolinite/pH 7	3
0.235	0.821	1x10 ⁻⁸ to 1x10 ⁻²	Na/Kaolinite/pH 10	3
3.03x10 ⁻²	0.804	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Kaolinite/pH 2	3
0.135	0.845	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Kaolinite/pH 4	3
0.247	0.881	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Kaolinite/pH 7	3
8.71x10 ⁻³	0.694	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Kaolinite/pH 10	3
1.02x10 ⁻⁴	0.503	1x10 ⁻⁸ to 1x10 ⁻²	Na/Montmorillonite/pH 2	3
1.05x10 ⁻²	0.709	1x10 ⁻⁸ to 1x10 ⁻²	Na/Montmorillonite/pH 4	3
3.17x10 ⁻²	0.755	1x10 ⁻⁸ to 1x10 ⁻²	Na/Montmorillonite./pH 7	3
0.224	0.815	1x10 ⁻⁸ to 1x10 ⁻²	Na/Montmorillonite/pH 10	3
0.241	0.839	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Montmorillonite/pH 2	3
0.481	0.897	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Montmorillonite/pH 4	3
1.84	0.938	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Montmorillonite/pH 7	3
0.274	0.82	1x10 ⁻⁸ to 1x10 ⁻²	Ca/Montmorillonite/pH 10	3
3.40x10 ⁻²	0.51	1x10 ⁻⁷ to 1x10 ⁻³	Granite/pH 8.2	4
4.90x10 ⁻²	0.5	1x10 ⁻⁷ to 1x10 ⁻³	Granite/pH 8.2	4
4.00x10 ⁻²	0.5			5

¹ Parameters “a” and “b” are fitting parameters in the Freundlich equation.

² References: 1 = Fukui, 1990; 2 = Konishi *et al.*, 1988; 3 = Adeleye *et al.*, 1994; 4 = Serne *et al.*, 1993; 5 = Shiao *et al.*, 1979.

Table D.9. Descriptive statistics of the cesium Freundlich equations (Table D.8) reported in the literature.

Statistic	a	b
Mean	252	0.696
Standard Error	150.2	0.029
Median	0.222	0.720
Mode	NA	0.815
Standard Deviation	1019	0.198
Sample Variance	1038711	0.039
Range	6070	1.087
Minimum	0.000013	0.013
Maximum	6070	1.1
95% Confidence Level	302	0.059

Using the medians of the a and b parameters from the literature, we come up with the overall equation:

$$C_{s_{\text{adsorbed}}} = 0.222(C_{s_{\text{solution}}})^{0.720} \quad (\text{D.3})$$

This equation is plotted in Figure D.4. Using $C_{s_{\text{adsorbed}}}$ and $C_{s_{\text{solution}}}$ from equation D.3, a K_d value can be calculated according to equations D.4,

$$K_d = C_{s_{\text{adsorbed}}} / C_{s_{\text{solution}}} \quad (\text{D.4})$$

Cesium K_d values calculated from Equations D.3 and D.4 are presented in Figure D.5.

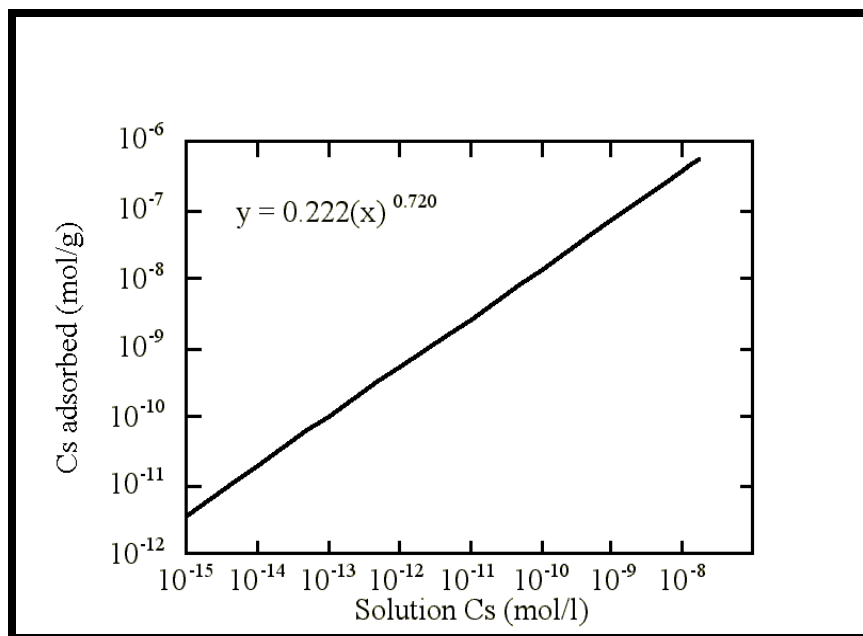


Figure D.4. Generalized cesium Freundlich equation (Equation D.3) derived from the literature.

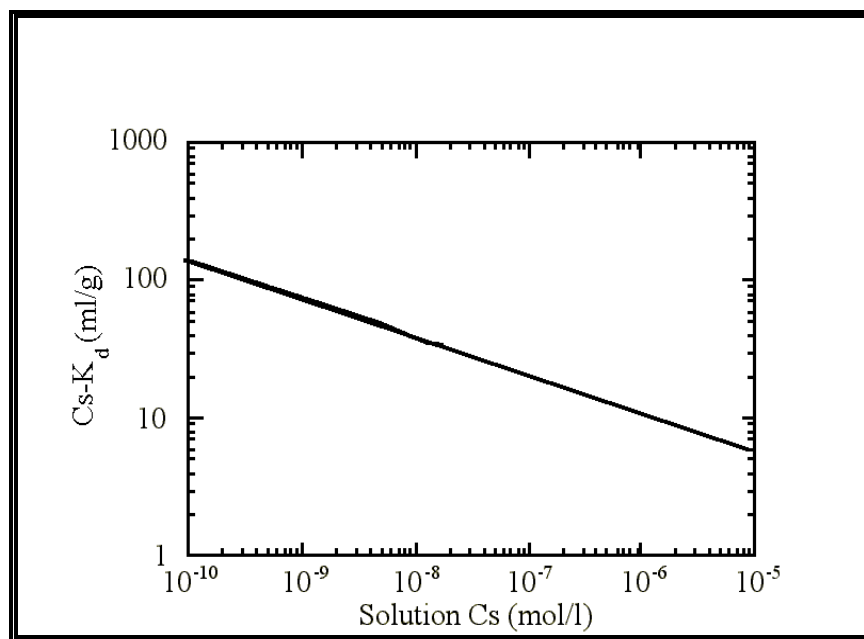


Figure D.5. Cesium K_d values calculated from generalized Freundlich equation (Equations D.3 and D.4) derived from the literature.

D.2.6 Approach to Selecting K_d Values for Look-up Table

Linear regression analyses were conducted with data collected from the literature. These analyses were used as guidance for selecting appropriate K_d values for the look-up table. The K_d values used in the look-up tables could not be based entirely on statistical consideration because the statistical analysis results were occasionally nonsensible. For example, the data showed a negative correlation between pH and CEC, and pH and cesium K_d values. These trends contradict well established principles of surface chemistry. Instead, the statistical analysis was used to provide guidance as to the approximate range of values to use and to identify meaningful trends between the cesium K_d values and the solid phase parameters. Thus, the K_d values included in the look-up table were in part selected based on professional judgment. Again, only low-ionic strength solutions, such as groundwaters, were considered; thus no solution variables were included.

Two look-up tables containing cesium K_d values were created. The first table is for systems containing low concentrations (*i.e.*, less than about 5 percent of the clay-size fraction) of mica-like minerals (Table D.10). The second table is for systems containing high concentrations of mica-like minerals (Table D.11). For both tables, the user will be able to reduce the range of possible cesium K_d values with knowledge of either the CEC or the clay content.

The following steps were taken to assign values to each category in the look-up tables. A relation between CEC and clay content was established using data presented in this section. Three CEC and clay content categories were selected. The limits of these categories were arbitrarily assigned. The central estimates for the <5 percent mica look-up table (Table D.10) were assigned using the CEC/cesium K_d equation in Figure D.1. The central estimates for the >5 percent mica look-up table (Table D.11) were assigned by multiplying the central estimates from Table D.10 by a factor of 2.5. The 2.5 scaler was selected based on relationships existing in the values in the data set and in Table D.6. Finally, the lower and upper limits for these central estimates were estimated based on the assumption that there was 2.5 orders of magnitude variability associated with the central estimates. The variability was based on visual inspection of a number of figures containing the cesium K_d values, including Figure D.1.

The calculations and equations used to estimate the central, minimum, and maximum estimates used in the look-up tables are presented in Table D.12.

Table D.10. Estimated range of K_d values (ml/g) for cesium based on CEC or clay content for systems *containing <5% mica-like minerals* in clay-size fraction and $<10^{-9}$ M aqueous cesium. [Table pertains to systems consisting of natural soils (as opposed to pure mineral phases), low ionic strength (< 0.1 M), low humic material concentrations (<5 mg/l), no organic chelates (such as EDTA), and oxidizing conditions]

K_d (ml/g)	CEC (meq/100 g) / Clay Content (wt.%)		
	<3 / <4	3 - 10 / 4 - 20	10 - 50 / 20 - 60
Central	200	500	1,500
Minimum	10	30	80
Maximum	3,500	9,000	26,700

Table D.11. Estimated range of K_d values (ml/g) for cesium based on CEC or clay content for systems *containing >5% mica-like minerals* in Clay-size fraction and $<10^{-9}$ M aqueous cesium. [Table pertains to systems consisting of natural soils (as opposed to pure mineral phases), low ionic strength (< 0.1 M), low humic material concentrations (<5 mg/l), no organic chelates (such as EDTA), and oxidizing conditions.]

K_d (ml/g)	CEC (meq/100 g) / Clay Content (wt.%)		
	<3 / <4	3 - 10 / 4 - 20	10 - 50 / 20 - 60
Central	500	1250	3750
Minimum	30	70	210
Maximum	9,000	22,000	66,700

Table D.12. Calculations for values used in look-up table.

Mica Concentration in Clay Fraction (%)	Clay Content (wt.%)	CE ¹ (ml/g)	Logarithm Scale		Base-10 Scale	
			Log CE	Lower Limit (Log CE)/2	Lower Limit $10^{(\log \text{CE})/2}$ (ml/g)	Upper Limit $10^{\log \text{CE} + (\log \text{CE})/2}$ (ml/g)
<5	<4	200	2.301	1.151	14	2,828
<5	4 -20	500	2.699	1.349	22	11,180
<5	20 - 60	1,500	3.176	1.588	39	58,095
>5	<4	500	2.699	1.349	22	11,180
>5	4 -20	1,250	3.097	1.548	35	44,194
>5	20 - 60	3,750	3.574	1.787	61	229,640
¹ CE = Central Estimate						

D.3.0 K_d Data Set for Soils and Pure Mineral Phases

Table D.13 lists the available cesium K_d values identified for experiments conducted with soils and pure mineral phases.

Table D.13. Cesium K_d data base for soils and pure mineral phases

Cesium K _d (ml/g)	Clay (wt. %)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
247			6.2			1.90x10 ⁻²	Gorleben Groundwater	Gorleben Sediment	1
62			6.2			1.42x10 ⁻¹		Gorleben Sediment	1
22			6.2			5.94x10 ⁻¹		Gorleben Sediment	1
16			6.2			1.05		Gorleben Sediment	1
12			6.2			1.53		Gorleben Sediment	1
167			8.1		189	5.20x10 ⁻³	Groundwater-1	S1: Quartz, Kaolinite, Plagioclase	2
1			7.8		113	5.20x10 ⁻³	Groundwater-2	S2:Quartz, Kaolinite, Dolomite	2
1500			9.3	60	70	1.00x10 ⁻¹	Water pH 9.3	Bentonite	3
160			2.4	60	70	1.00x10 ⁻¹	Groundwater pH 2.4	Bentonite	3
1100			9.3	60	70	1.00x10 ⁻¹	Groundwater pH 9.3	Bentonite	3
4100			6.1	20	130	1.00x10 ⁻¹	Water pH 6.1	Takadate loam	3
1400			7.7	20	130	1.00x10 ⁻¹	Groundwater pH 7.7	Takadate loam	3
1100			6.6	70	60	1.00x10 ⁻¹	Water pH 6.6	Hachinohe loam	3
280			8.3	70	60	1.00x10 ⁻¹	Groundwater pH 8.3	Hachinohe loam	3
237			8.2	2	22	1.00x10 ⁻³		ym-22	4
8220			8.2	109	103	1.00x10 ⁻³		ym-38	4
325			8.2	6	43	1.00x10 ⁻³		ym-45	4
22100			8.2	51	19	1.00x10 ⁻³		ym-48	4
35800			8.2	107		1.00x10 ⁻³		ym-49	4
42600			8.2	107		1.00x10 ⁻³		ym-49	4
205			8.2	4		1.00x10 ⁻³		ym-54	4

Cesium Kd (ml/g)	Clay (wt.%)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
15200			8.4		31	1.00x10 ⁻³	low salts	JA-18	4
8440			8.3		31	1.00x10 ⁻³	hi salts	JA-18	4
143			8.2		8	1.00x10 ⁻³	low salts	JA-32	4
73			8.5		8	1.00x10 ⁻³	hi salts	JA-32	4
1390			8.4		100	1.00x10 ⁻³	low salts	JA-37	4
757			8.5		100	1.00x10 ⁻³	hi salts	JA-37	4
95		15	4			4.20x10 ⁻⁴	0.005 M Na	Savannah River	5
120		15	5.5			4.20x10 ⁻⁴	0.005 M Na	Savannah River	5
130		15	6.7			4.20x10 ⁻⁴	0.005 M Na	Savannah River	5
130		15	7			4.20x10 ⁻⁴	0.005 M Na	Savannah River	5
150		15	8.5			4.20x10 ⁻⁴	0.005 M Na	Savannah River	5
160		15	10.2			4.20x10 ⁻⁴	0.005 M Na	Savannah River	5
72		3	4			4.20x10 ⁻⁴	0.005 M Na	4-Mile Creek	5
79		3	5.5			4.20x10 ⁻⁴	0.005 M Na	4-Mile Creek	5
75		3	6.7			4.20x10 ⁻⁴	0.005 M Na	4-Mile Creek	5
98		3	7			4.20x10 ⁻⁴	0.005 M Na	4-Mile Creek	5
83		3	8.5			4.20x10 ⁻⁴	0.005 M Na	4-Mile Creek	5
33		4	4			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	5
37		4	5.5			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	5
40		4	7			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	5
39		4	8.5			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	5
50		4	10.2			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	5
27		2	4			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	5
25		2	5.5			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	5
26		2	6.7			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	5
26		2	7			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	5
38		2	8.5			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	5
39		2	10.2			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	5
88		4	4			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	5
92		4	5.5			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	5
93		4	6.7			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	5

Cesium Kd (ml/g)	Clay (wt.%)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
85		4	7			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	5
94		4	8.5			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	5
101		4	10.2			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	5
88		5	4			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	5
89		5	5.5			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	5
90		5	6.7			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	5
84		5	7			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	5
101		5	10.2			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	5
22		2	4			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	5
31		2	5.5			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	5
37		2	6.7			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	5
40		2	7			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	5
78		2	10.2			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	5
27			8.25	1.83	17.7	2.72x10 ²	0.002 M Groundwater	Umtanum Basalt	6
329			8.25	1.83	17.7	2.90x10 ⁻¹	0.002 M Groundwater	Umtanum Basalt	6
960			8.25	1.83	17.7	1.03x10 ⁻³	0.002 M Groundwater	Umtanum Basalt	6
1088			8.25	1.83	17.7	9.11x10 ⁻⁶	0.002 M Groundwater	Umtanum Basalt	6
1084			8.25	1.83	17.7	1.87x10 ⁻⁶	0.002 M Groundwater	Umtanum Basalt	6
28			8.6	1.83	17.7	2.63x10 ²	0.013 M Groundwater	Umtanum Basalt	6
289			8.6	1.83	17.7	3.31x10 ⁻¹	0.013 M Groundwater	Umtanum Basalt	6
951			8.6	1.83	17.7	1.05x10 ⁻³	0.013 M Groundwater	Umtanum Basalt	6
1022			8.6	1.83	17.7	9.77x10 ⁻⁶	0.013 M Groundwater	Umtanum Basalt	6
1025			8.6	1.83	17.7	1.95x10 ⁻⁶	0.013 M Groundwater	Umtanum Basalt	6
18			8.2	1.5	10.3	3.61x10 ²	0.002 M Groundwater	Flow E Basalt	6
189			8.2	1.5	10.3	5.00x10 ⁻¹	0.002 M Groundwater	Flow E Basalt	6

Cesium Kd (ml/g)	Clay (wt.%)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
418			8.2	1.5	10.3	2.34x10 ⁻³	0.002 M Groundwater	Flow E Basalt	6
450			8.2	1.5	10.3	2.17x10 ⁻⁵	0.002 M Groundwater	Flow E Basalt	6
487			8.2	1.5	10.3	3.98x10 ⁻⁶	0.002 M Groundwater	Flow E Basalt	6
20			8.7	1.5	10.3	3.39x10 ²	0.013 M Groundwater	Flow E Basalt	6
214			8.7	1.5	10.3	4.47x10 ⁻¹	0.013 M Groundwater	Flow E Basalt	6
488			8.7	1.5	10.3	2.00x10 ⁻³	0.013 M Groundwater	Flow E Basalt	6
549			8.7	1.5	10.3	1.78x10 ⁻⁵	0.013 M Groundwater	Flow E Basalt	6
617			8.7	1.5	10.3	3.24x10 ⁻⁶	0.013 M Groundwater	Flow E Basalt	6
48			8.3	4.84	31.2	1.71x10 ²	0.002 M Groundwater	Pomona Basalt	6
460			8.3	4.84	31.2	2.13x10 ⁻¹	0.002 M Groundwater	Pomona Basalt	6
1111			8.3	4.84	31.2	8.30x10 ⁻⁴	0.002 M Groundwater	Pomona Basalt	6
1466			8.3	4.84	31.2	6.37x10 ⁻⁶	0.002 M Groundwater	Pomona Basalt	6
1281			8.3	4.84	31.2	1.39x10 ⁻⁶	0.002 M Groundwater	Pomona Basalt	6
56			8.55	4.84	31.2	1.51x10 ²	0.013 M Groundwater	Pomona Basalt	6
389			8.55	4.84	31.2	2.57x10 ⁻¹	0.013 M Groundwater	Pomona Basalt	6
853			8.55	4.84	31.2	1.17x10 ⁻³	0.013 M Groundwater	Pomona Basalt	6
952			8.55	4.84	31.2	1.05x10 ⁻⁵	0.013 M Groundwater	Pomona Basalt	6
908			8.55	4.84	31.2	1.74x10 ⁻⁶	0.013 M Groundwater	Pomona Basalt	6
212			8.3	71	646	4.50x10 ¹	0.002 M Groundwater	Smectite	6
1080			8.3	71	646	9.17x10 ⁻¹	0.002 M Groundwater	Smectite	6

Cesium Kd (ml/g)	Clay (wt.%)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
13042			8.3	71	646	7.66x10 ⁻⁵	0.002 M Groundwater	Smectite	6
9794			8.3	71	646	1.00x10 ⁻⁶	0.002 M Groundwater	Smectite	6
25000			8.3	71	646	7.00x10 ⁻⁸	0.002 M Groundwater	Smectite	6
224			9.2	71	646	4.27x10 ⁻¹	0.013 M Groundwater	Smectite	6
2136			9.2	71	646	4.68x10 ⁻²	0.013 M Groundwater	Smectite	6
5882			9.2	71	646	1.70x10 ⁻⁴	0.013 M Groundwater	Smectite	6
8547			9.2	71	646	1.17x10 ⁻⁶	0.013 M Groundwater	Smectite	6
8333			9.2	71	646	2.40x10 ⁻⁷	0.013 M Groundwater	Smectite	6
5000	24		4.4	82		6.80x10 ⁻²	1x10 ⁻⁶ M KCl	Batcombe	7
5000	24		4.4	82		6.80x10 ⁻²	1x10 ⁻⁵ M KCl	Batcombe	7
4700	24		4.4	82		6.80x10 ⁻²	1x10 ⁻⁴ M KCl	Batcombe	7
2000	24		4.4	82		6.80x10 ⁻²	1x10 ⁻³ M KCl	Batcombe	7
9000	42		6.2	72		6.80x10 ⁻²	1x10 ⁻⁶ M KCl	Tedburn	7
8000	42		6.2	72		6.80x10 ⁻²	1x10 ⁻⁵ M KCl	Tedburn	7
9000	42		6.2	72		6.80x10 ⁻²	1x10 ⁻⁴ M KCl	Tedburn	7
2000	42		6.2	72		6.80x10 ⁻²	1x10 ⁻³ M KCl	Tedburn	7
1050	42		7.3	54		6.80x10 ⁻²	1x10 ⁻⁶ M KCl	Teigngrace	7
1025	42		7.3	54		6.80x10 ⁻²	1x10 ⁻⁵ M KCl	Teigngrace	7
1000	42		7.3	54		6.80x10 ⁻²	1x10 ⁻⁴ M KCl	Teigngrace	7
800	42		7.3	54		6.80x10 ⁻²	1x10 ⁻³ M KCl	Teigngrace	7
11000				130		1.00x10 ⁻⁷	Water	Itago Tuff	8
10000				97		1.00x10 ⁻⁷	Water	Ohya Tuff	8
5000				2.4		1.00x10 ⁻⁷	Water	Sandstone	8
2000				1.9		1.00x10 ⁻⁷	Water	Shale	8
6000				1.9		1.00x10 ⁻⁷	Water	Augite Audesite	8
500				1.2		1.00x10 ⁻⁷	Water	Plagio Rhyolite	8
5800				0.75		1.00x10 ⁻⁷	Water	Olivine Basalt	8

Cesium Kd (ml/g)	Clay (wt.%)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
900				0.54		1.00x10 ⁻⁷	Water	Ionada Granite	8
260				0.35		1.00x10 ⁻⁷	Water	Rokka Granite	8
80				0.033		1.00x10 ⁻⁷	Water	Limestone	8
2200				1.2		1.00x10 ⁻⁷	Water	Biotite	8
1800				0.93		1.00x10 ⁻⁷	Water	Chlorite	8
630				0.33		1.00x10 ⁻⁷	Water	Hornblende	8
420				0.11		1.00x10 ⁻⁷	Water	Grossular	8
460				0.0067		1.00x10 ⁻⁷	Water	Forsterite	8
30				0.0034		1.00x10 ⁻⁷	Water	K-feldspar	8
89				0.0032		1.00x10 ⁻⁷	Water	Albite	8
31				0.00098		1.00x10 ⁻⁷	Water	Quartz	8
1				0.15849		1.00x10 ⁻¹		Calcite	9
3				0.19953		1.00x10 ⁻¹		Apatite	9
6				1.58489		1.00x10 ⁻¹		Hematite	9
13				1.77828		1.00x10 ⁻¹		Orthoclase	9
16				5.62341		1.00x10 ⁻¹		Serpentine	9
200				7.94328		1.00x10 ⁻¹		Hornblende	9
631				39.8107		1.00x10 ⁻¹		Biotite	9
794				63.0957		1.00x10 ⁻¹		Muscovite	9
100				4.46684		1.00x10 ⁻¹		Gneiss	9
16				6.30957		1.00x10 ⁻¹		Diabase	9
158				10		1.00x10 ⁻¹		Stripa Granite	9
562				11.2202		1.00x10 ⁻¹		Finsjo Granite	9
900			5			1.00x10 ⁻¹		Biotite	9
790			7			1.00x10 ⁻¹		Biotite	9
700			9			1.00x10 ⁻¹		Biotite	9
2			5			1.00x10 ⁻¹		Hematite	9
4			7			1.00x10 ⁻¹		Hematite	9
8			9			1.00x10 ⁻¹		Hematite	9
40			5			1.00x10 ⁻¹		Hornblende	9
100			7			1.00x10 ⁻¹		Hornblende	9

Cesium Kd (ml/g)	Clay (wt.%)	Mica (%)	pH	CEC ^a (meq/100 g)	SA ¹ (m ² /g)	Aqueous Cs (μM)	Background Aqueous	Soil and Mineral Phase ID and Information	Ref ²
240			9			1.00x10 ⁻¹		Hornblende	9
3			5			1.00x10 ⁻¹		Magnetite	9
5			7			1.00x10 ⁻¹		Magnetite	9
9			9			1.00x10 ⁻¹		Magnetite	9
700			5			1.00x10 ⁻¹		Muscovite	9
810			7			1.00x10 ⁻¹		Muscovite	9
840			9			1.00x10 ⁻¹		Muscovite	9
7			5			1.00x10 ⁻¹		Orthoclase	9
14			7			1.00x10 ⁻¹		Orthoclase	9
7			9			1.00x10 ⁻¹		Orthoclase	9
52000				127		1.67x10 ⁻⁶	Deionized Water	Vermiculite	10
26000				20		1.67x10 ⁻⁶	Deionized Water	Illite	10
2500				11.2		1.67x10 ⁻⁶	Deionized Water	Kaolinite	10
2700				127		1.67x10 ⁻⁶	0.1 N NaCl	Vermiculite	10
28600				20		1.67x10 ⁻⁶	0.1 N NaCl	Illite	10
94				11.2		1.67x10 ⁻⁶	0.1 N NaCl	Kaolinite	10
7						1.00x10 ⁻⁷	Groundwater	Hanford Vadose Sediment	11
12						1.00x10 ⁻⁷	Groundwater	Hanford Vadose Sediment	11
2190	4	9	7.7			8.40x10 ⁻³	Groundwater	Sediment CGS-1	12
7610	5	12	8.2			8.40x10 ⁻³	Groundwater	Sediment TBS-1	12
620	6	9	7.9			8.40x10 ⁻³	Groundwater	Sediment Trench-8	12

¹ CEC = cation exchange capacity; SA = surface area.

² References: 1 = Lieser and Steinkopff, 1989; 2 = Lieser *et al.*, 1986; 3 = Konishi *et al.*, 1988; 4 = Vine *et al.*, 1980; 5 = Elprince *et al.*, 1977; 6 = Ames *et al.*, 1982; 7 = Staunton, 1994; 8 = Akiba *et al.*, 1989; 9 = Torstenfelt *et al.*, 1982; 10 = Tamura, 1972; 11 = Routson *et al.*, 1980; 12 = Serne *et al.*, 1993.

D.4.0 Data Set for Soils

Table D.14 lists the available cesium K_d values identified for experiments conducted with only soils.

Table D.14. Cesium K_d data set for soils only.

Cesium K_d (ml/g)	Clay (wt%)	Mica (%)	pH	CEC ^(a) (meq/100 g)	SA ¹ (m ² /g)	Cs (μ M)	Aqueous Phase	Soil ID and Information	Ref. ²
247			6.2			1.90×10^{-2}	Gorleben Groundwater	Gorleben Sediment	1
62			6.2			1.42×10^{-1}		Gorleben Sediment	1
22			6.2			5.94×10^{-1}		Gorleben Sediment	1
4100			6.1	20	130	1.00×10^{-1}	Water pH 6.1	Takadate Loam	4
1400			7.7	20	130	1.00×10^{-1}	Groundwater pH 7.7	Takadate Loam	4
1100			6.6	70	60	1.00×10^{-1}	Water pH 6.6	Hachinohe Loam	4
280			8.3	70	60	1.00×10^{-1}	Groundwater pH 8.3	Hachinohe loam	4
95		15	4			4.20×10^{-4}	0.005 M Na	Sav. River Site Sediment	6
120		15	5.5			4.20×10^{-4}	0.005 M Na	Sav. River Site Sediment	6
130		15	6.7			4.20×10^{-4}	0.005 M Na	Sav. River Site Sediment	6
130		15	7			4.20×10^{-4}	0.005 M Na	Sav. River Site Sediment	6
150		15	8.5			4.20×10^{-4}	0.005 M Na	Sav. River Site Sediment	6
160		15	10.2			4.20×10^{-4}	0.005 M Na	Sav. River Site Sediment	6
72		3	4			4.20×10^{-4}	0.005 M Na	4-Mile Creek Sediment	6
79		3	5.5			4.20×10^{-4}	0.005 M Na	4-Mile Creek Sediment	6
75		3	6.7			4.20×10^{-4}	0.005 M Na	4-Mile Creek Sediment.	6
98		3	7			4.20×10^{-4}	0.005 M Na	4-Mile Creek Sediment.	6
83		3	8.5			4.20×10^{-4}	0.005 M Na	4-Mile Creek Sediment.	6
33		4	4			4.20×10^{-4}	0.005 M Na	Par Pond Soil	6

Cesium K _d (ml/g)	Clay (wt%)	Mica (%)	pH	CEC ^(a) (meq/100 g)	SA ¹ (m ² /g)	Cs (μM)	Aqueous Phase	Soil ID and Information	Ref. ²
37		4	5.5			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	6
40		4	7			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	6
39		4	8.5			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	6
50		4	10.2			4.20x10 ⁻⁴	0.005 M Na	Par Pond Soil	6
27		2	4			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	6
25		2	5.5			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	6
26		2	6.7			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	6
26		2	7			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	6
38		2	8.5			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	6
39		2	10.2			4.20x10 ⁻⁴	0.005 M Na	Steel Creek Soil	6
88		4	4			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Soil	6
92		4	5.5			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Sediment	6
93		4	6.7			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Sediment	6
85		4	7			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Sediment	6
94		4	8.5			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Sediment	6
101		4	10.2			4.20x10 ⁻⁴	0.005 M Na	Lower 3 Runs Sediment	6
88		5	4			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	6
89		5	5.5			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	6
90		5	6.7			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	6
84		5	7			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	6
101		5	10.2			4.20x10 ⁻⁴	0.005 M Na	Pen Branch Soil	6
22		2	4			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	6
31		2	5.5			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	6
37		2	6.7			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	6
40		2	7			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	6
78		2	10.2			4.20x10 ⁻⁴	0.005 M Na	Upper 3 Runs Soil	6
7						1.00x10 ⁻⁷	Groundwater	Hanford Vadose Sediment	8
12						1.00x10 ⁻⁷	Groundwater	Hanford Vadose Sediment	8

Cesium K _d (ml/g)	Clay (wt%)	Mica (%)	pH	CEC ^(a) (meq/100 g)	SA ¹ (m ² /g)	Cs (μM)	Aqueous Phase	Soil ID and Information	Ref. ²
3,000		6	7.6	3	8.6	1.00x10 ⁻¹	Groundwater	Sediment A	10
4,800		7.5	5.9	4.3	12.2	1.00x10 ⁻¹	Groundwater	Sediment B	10
3,100		8	6.6	4.7	14.7	1.00x10 ⁻¹	Groundwater	Sediment C	10
3,000		5	8	2.6	6.6	1.00x10 ⁻¹	Groundwater	Sediment D	10
2,190	4	9	7.7			8.40x10 ⁻³	Groundwater	Sediment CGS-1	11
7,610	5	12	8.2			8.40x10 ⁻³	Groundwater	Sediment TBS-1	11
620	6	9	7.9			8.40x10 ⁻³	Groundwater	Sediment Trench-8	11

¹ CEC = cation exchange capacity; SA = surface area.
² 1 = Lieser and Steinkopff, 1989; 4 = Konishi *et al.*, 1988; 6 = Elprince *et al.*, 1977; 8 = Routson *et al.*, 1980; 10 = Legoux *et al.*, 1992; 11 = Serne *et al.*, 1993.

D.5.0 References

- Adeleye, S. A., P. G. Clay, and M. O. A. Oladipo. 1994. "Sorption of Caesium, Strontium and Europium Ions on Clay Minerals." *Journal of Materials Science*, 29:954-958.
- Akiba, D., and H. Hashimoto. 1990. "Distribution Coefficient of Strontium on Variety of Minerals and Rocks." *Journal of Nuclear Science and Technology*, 27:275-279.
- Akiba, D., H. Hashimoto, and T. Kanno. 1989. "Distribution Coefficient of Cesium and Cation Exchange Capacity of Minerals and Rocks." *Journal of Nuclear Science and Technology*, 26:1130-1135.
- Ames, L., and D. Rai. 1978. *Radionuclide Interactions with Soil and Rock Media. Volume 1: Processes Influencing Radionuclide Mobility and Retention, Element Chemistry and Geochemistry, Conclusions and Evaluation*. PB-292 460, Pacific Northwest Laboratory, Richland, Washington.
- Ames, L. L., J. E. McGarrah, B. A. Walker, and P. F. Salter. 1982. "Sorption of Uranium and Cesium by Hanford Basalts and Associated Secondary Smectite." *Chemical Geology*, 35:205-225.
- Comans, R. N. J., J. J. Middelburg, J. Zonderhuis, J. R. W. Woittiez, G. J. De Lange, H. A. Das, C. H. Van Der Weijden. 1989. "Mobilization of Radiocaesium in Pore Water in Lake Sediments." *Nature*, 367-369.
- Cremers, A., A. Elsen. P. De Preter, and A. Maes. 1988. "Quantitative Analysis of Radiocaesium Retention in Soils." *Nature*, 335:247-249.

- Bruggenwert, M. G. M., and A. Kamphorst. 1979. "Survey of Experimental Information on Cation Exchange in Soil Systems." In *Soil Chemistry: B. Physico-Chemical Models*, G. H. Bolt (ed.), Elsevier Scientific Publishing Company, New York, New York.
- Dahlman, R. C., E. A. Bondietti, and L. D. Eyman. 1976. "Biological Pathways and Chemical Behavior of Plutonium and Other Actinides in the Environment." In *Actinides in the Environment*, A. M. Friedman (ed.), pp. 47-80. ACS Symposium Series 35, American Chemical Society, Washington, D.C.
- Douglas, L. A. 1989. "Vermiculites." In *Minerals in Soil Environments*, J. B. Dixon and S. B. Week (eds.), Second Edition, pp. 635-674, Soil Science Society of America, Madison, Wisconsin.
- Elprince, A. M., C. I. Rich, and D. C. Martens. 1977. "Effect of Temperature and Hydroxy Aluminum Interlayers on the Adsorption of Trace Radioactive Cesium by Sediments near Water-Cooled Nuclear Reactors." *Water Resources Research*, 13:375-380.
- Erten, H. N., S. Aksoyoglu, S. Hatipoglu, and H. Göktürk. 1988. "Sorption of Cesium and Strontium on Montmorillonite and Kaolinite." *Radiochimica Acta*, 44/45:147-155.
- Evans, D. W., J. J. Alberts, and R. A. Clark. 1983. "Reversible Ion-Exchange Fixation of Cesium-137 Leading to Mobilization from Reservoir Sediments." *Geochimica et Cosmochimica Acta*, 47:1041-1049.
- Francis, C. W., and F. S. Brinkley. 1976. "Preferential Adsorption of ^{137}Cs to Micaceous Minerals in Contaminated Freshwater Sediments." *Nature*, 260:511-513.
- Fukui, M. 1990. "Desorption Kinetics and Mobility of Some Radionuclides in Sediments." *Health Physics*, 59:879-889.
- Hartman, M. J., and P. E. Dresel. 1997. *Hanford Site Groundwater Monitoring for Fiscal Year 1996*. PNNL-11470, Pacific Northwest National Laboratory, Richland, Washington.
- Hem, J. D. 1985. *Study and Interpretation of the Chemical Characteristics of Natural Water*. Water Supply Paper 2254, U.S. Geological Survey, Alexandria, Virginia.
- Inch, K. J. and R. W. D. Killey. 1987. "Surface Area and Radionuclide Sorption in Contaminated Aquifers." *Water Pollution Research Journal of Canada*, 22:85-98.
- Konishi, M., K. Yamamoto, T. Yanagi, and Y. Okajima. 1988. "Sorption Behavior of Cesium, Strontium and Americium Ions on Clay Materials." *Journal of Nuclear Science and Technology*. 25:929-933.
- Legoux, Y., G. Blain, R. Guillaumont, G. Ouzounian, L. Brillard, and M. Hussonnois. 1992. " K_d Measurements of Activation, Fission, and Heavy Elements in Water/Solid Phase Systems." *Radiochimica Acta*, 58/59:211-218.

- Li, Y., L. Burkhardt, M. Buchholtz, P. O'Hara, and P. H. Santschi. 1994. "Partition of Radiotracers Between Suspended Particles and Seawater." *Geochimica et Cosmochimica Acta*, 48:2011-2019.
- Lieser, K. H., B. Gleitsmann, and Th. Steinkopff. 1986. "Sorption of Trace Elements or Radionuclides in Natural Systems Containing Groundwater and Sediments." *Radiochimica Acta*, 40:33-37.
- Lieser, K. H., and Th. Steinkopff. 1989. "Sorption Equilibria of Radionuclides or Trace Elements in Multicomponent Systems." *Radiochimica Acta*, 47:55-61.
- Neter, J., and W. Wasserman. 1974. *Applied Linear Statistical Models*. Richard D. Irwin, Inc. Homewood, Illinois.
- Ohnuki, T. 1991. "Characteristics of Migration of ^{85}Sr and ^{137}Cs in Alkaline Solution Through Sandy Soil." *Material Research Society Proceedings*, 212:609-616.
- Petersen, L. W., P. Moldrup, O. H. Jacobsen, and D. E. Rolston. 1996. "Relations Between Specific Surface Area and Soils Physical and Chemical Properties." *Soil Science*, 161:9-21.
- Rhodes, D. W., and J. L. Nelson. 1957. *Disposal of Radioactive Liquid Wastes From the Uranium Recovery Plant*. HW-54721, Westinghouse Hanford Company, Richland, Washington.
- Routson, R. C., G. S. Barney, and R. M. Smith. 1980. *Hanford Site Sorption Studies for the Control of Radioactive Wastes: A Review*. WHO-SA-155, Rev. 1, Rockwell Hanford Operations, Richland, Washington.
- Satmark, B., and Y. Albinsson. 1991. "Sorption of Fission Products on Colloids Made of Naturally Occurring Minerals and the Stability of these Colloids." *Radiochimica Acta*, 58/59:155-161.
- Sawhney, B. L. 1972. "Selective Sorption and Fixation of Cations by Clay Minerals: A Review." *Clays and Clay Minerals*, 20:93-100.
- Serne, R. J., J. L. Conca, V. L. LeGore, K. J. Cantrell, C. W. Lindenmeier, J. A. Campbell, J. E. Amonette, and M. I. Wood. 1993. *Solid-Waste Leach Characteristics and Contaminant-Sediment Interactions. Volume 1: Batch Leach and Adsorption Tests and Sediment Characterization*. PNL-8889, Pacific Northwest National Laboratory, Richland, Washington.
- Serne, R. J., and V. L. LeGore. 1996. *Strontium-90 Adsorption-Desorption Properties and Sediment Characterization at the 100 N-Area*. PNL-10899, Pacific Northwest National Laboratory, Richland, Washington.

- Shiao, S. Y., P. Rafferty, R. E. Meyer, and W. J. Rogers. 1979. "Ion-Exchange Equilibria Between Montmorillonite and Solutions of Moderate-to-High Ionic Strength." In *Radioactive Waste in Geologic Storage*, S. Fried (ed.), pp. 297-324, ACS Symposium Series 100, American Chemical Society, Washington, D.C.
- Smith, J. T., and R. N. J. Comans. 1996. "Modelling the Diffusive Transport and Remobilization of ^{137}Cs in Sediments: The Effects of Sorption Kinetics and Reversibility." *Geochimica et Cosmochimica Acta*, 60:995-1004.
- Sposito, G. 1984. *The Surface Chemistry of Soils*. Oxford University Press, New York, New York.
- Sposito, G. 1989. *The Chemistry of Soils*. Oxford University Press, New York, New York.
- Staunton, S. 1994. "Adsorption of Radiocaesium on Various Soils: Interpretation and Consequences of the Effects of Soil:Solution Ratio and Solution Composition on the Distribution Coefficient." *European Journal of Soil Science*, 45:409-418.
- Streng, D. L., and S. R. Peterson. 1989. *Chemical Databases for the Multimedia Environmental Pollutant Assessment System*. PNL-7145, Pacific Northwest National Laboratory, Richland, Washington.
- Tamura, T. 1972. "Sorption Phenomena Significant in Radioactive-Waste Disposal." *Am. Assoc. Pet. Geol. Mem.*, 18:318-33.
- Torstenfelt, B. K. Andersson, and B. Allard. 1982. "Sorption of Strontium and Cesium on Rocks and Minerals." *Chemical Geology*, 36:128-137.
- Vine, E. N., R. D. Aguilar, B. P. Bayhurst, W. R. Daniels, S. J. DeVilliers, B. R. Erdal, F. O. Lawrence, S. Maestas, P. Q. Oliver, J. L. Thompson, and K. Wolfsberg. 1980. *Sorption-Desorption Studies on Tuff. II. A Continuation of Studies with Samples from Jackass Flats, Nevada and Initial Studies with Samples from Yucca Mountain, Nevada*. LA-8110-MS, Los Alamos National Laboratory, Los Alamos, New Mexico.